Int J Life Cycle Assess (2010) 15:260–271
DOI 10.1007/s11367-010-0164-7

LCA FOR ENERGY SYSTEMS

Energy system analysis of marginal electricity supply in consequential LCA

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Received: 11 April 2008 / Accepted: 24 December 2009 / Published online: 13 February 2010

Abstract
Background, aim and scope This paper discusses the identification of the environmental consequences of marginal electricity supplies in consequential life cycle assessments (LCA). According to the methodology, environmental characteristics can be examined by identifying affected activities, i.e. often the marginal technology. The present 'state-of the-art' method is to identify the long-term change in power plant capacity, known as the long-term marginal technology, and assume that the marginal supply will be fully produced at such capacity. However, the marginal change in capacity will have to operate as an integrated part of the total energy system. Consequently, it does not necessarily represent the marginal change in electricity supply, which is likely to involve a mixture of different production technologies. Especially when planning future sustainable energy systems involving combined heat and power (CHP) and fluctuating renewable energy sources, such issue becomes very important.
Materials and methods This paper identifies a business-as-usual (BAU) 2030 projection of the Danish energy system. With a high share of both CHP and wind power, such system can be regarded a front-runner in the development of future sustainable energy systems in general. A strict distinction is made between, on the one hand, marginal capacities, i.e. the long-term change in power plant capacities, and on the other, marginal supply, i.e. the changes in production given the combination of power plants and their individual marginal production costs. Detailed energy system analysis (ESA) simulation is used to identify the affected technologies, considering the fact that the marginal technology will change from one hour to another, depending on the size of electricity demand compared to, among others, wind power and CHP productions. On the basis of such input, a long-term yearly average marginal (YAM) technology is identified and the environmental impacts are calculated using data from ecoinvent.
Results The results show how the marginal electricity production is not based solely on the marginal change in capacity but can be characterised as a complex set of affected electricity and heat supply technologies. A long-term YAM technology is identified for the Danish BAU2030 system in the case of three different long-term marginal changes in capacity, namely coal, natural gas or wind power.
Discussion Four analyses and examples of YAMs have been used in order to present examples of the cause–effect chain between a change in demand for electricity and the installation of new capacity. In order to keep open the possibilities for further analysis of what can be considered the marginal technology, the results of four different situations are provided. We suggest that the technology mix with the installation of natural gas or coal power plant is applied as the marginal capacity.
Conclusions The environmental consequences of marginal changes in electricity supply cannot always be represented solely by long-term change in power plant capacity, known as the long-term marginal technology. The marginal change in capacity will have to operate as an integrated part of the total energy system and, consequently, in most energy systems, one will have to identify the long-term YAM technology in order to make an accurate evaluation of the environmental consequences.
Recommendations and perspectives This paper recommends a combination of LCA and ESA as a methodology

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for identifying a complex set of marginal technologies. The paper also establishes values for Danish marginal electricity production as a yearly average (YAM) that can be used in future LCA studies involving Danish electricity.

Keywords Consequential LCA · Danish electricity · Energy systems analysis · Marginal electricity · Methodology

1 Introduction

In life cycle assessment (LCA) studies, the impact of energy production is often of vital importance, and consequently, LCA data related to the provision of energy (heat and electricity) are essential to the analysis. In consequential LCA, the electricity data included represent the technology which is most likely to respond to a change in demand, often referred to as the marginal technology, typically coal or natural gas. In attributional LCA, the data included typically represent the average mix of supplying technologies. The present 'state-of-the-art' in consequential LCA is to identify the long-term change in power plant capacity and assume that the marginal supply will be fully produced at such capacity (Ekvall and Weidema 2004). In LCA literature, this long-term change in power plant capacity is referred to as the long-term marginal technology. Contrarily, the short-term marginal technology refers to the technologies which change due to short-term (hourly) changes in demand. The practice, to use the long-term marginal technology, has in recent years raised a debate on whether natural gas or coal is the marginal source of electricity production (Dones et al. 1998; Nordheim and Weidema 1999; Weidema et al. 1999; Frees and Weidema 1998; Curran et al. 2005). However, so far, no or only a few publications document a thorough and up-to-date identification of the marginal supply, e.g. see Frees and Weidema (1998). Therefore, not much scientifically based guidance on identifying the marginal supply of electricity exists. In addition to that, few LCAs have been identified taking into account the fact that the increase of one technology interferes with the rest of the energy system. For instance, if natural gas is considered the marginal and the capacity of natural gas is increased, this will lead to a change in the production of several technologies in the system (Eriksson et al. 2007). In Mathiesen et al. (2007, 2009), electricity data in consequential LCA were reviewed in a historical perspective through recent LCA studies and using waste as a case study. Here, it was recommended to improve the current practice by:

- using combined affected technologies, i.e. a complex set of marginal technologies;
- using a long-term perspective by identifying affected technologies in several possible future scenarios; and
- identifying the affected technologies on the basis of energy system analysis.

The purpose of this article was to identify the long-term yearly average changes in supply caused by a change in demand.

Referring to the term 'long-term marginal technology' mentioned earlier in this section, the concept 'long-term YAM technology', which is used here, does not assume that the marginal supply will be fully produced at the installed capacity caused by a change in demand. The long-term yearly average marginal (YAM) technology takes into account the fact that a change in capacity has to be adjusted to the existing energy system. If an electricity production system consists of a mixture of, e.g. coal and natural gas-fired power stations, such as the Danish one, the long-term marginal change in capacity will not necessarily determine only the marginal production. The reason for this is elaborated here.

The changes in annual electricity demand affect the supply of electricity differently from one hour to another. If a system is defined by a simple 50/50 mixture of coal-fired and natural gas-fired power plants and if, e.g. coal is the lowest cost production alternative, the lowest cost solution will be to meet the demands solely by coal, if possible. However, this may be possible only during low-demand hours, whilst during high-demand hours, the natural gas power plants will have to assist. The lowest cost marginal production will be coal at low-demand hours and natural gas at high-demand hours, and consequently, the average marginal change will be a mixture of the two. A short-term change in demand may lead to a long-term change in capacity, which will change such a mixture slightly, but it will hardly change the yearly average marginal supply neither to solely coal nor solely natural gas. Consequently, the long-term change in capacity, known as the long-term marginal technology, will not solely represent the marginal change in supply.

If wind power and combined heat and power (CHP) plants are involved, as is the case of Denmark, the mixture of marginal production differences becomes even more complex, as illustrated in Fig. 1. The diagram identifies changes in supply considering the fact that the marginal technology will change from one hour to another depending on the size of electricity demand compared to, among others, wind power and CHP productions. One important factor is whether or not the wind blows since this will determine wind power production. Another important factor is the season, if it is winter or summer, because this determines whether the district heating demand and thereby the CHP production is high or low.

In Fig. 1, CHP-min represents the technical minimum production of the thermal power stations in the electricity supply system. In order to secure grid stabilisation, etc., a certain minimum of steam turbine power stations will have to be operating. The rest of the units are prioritised

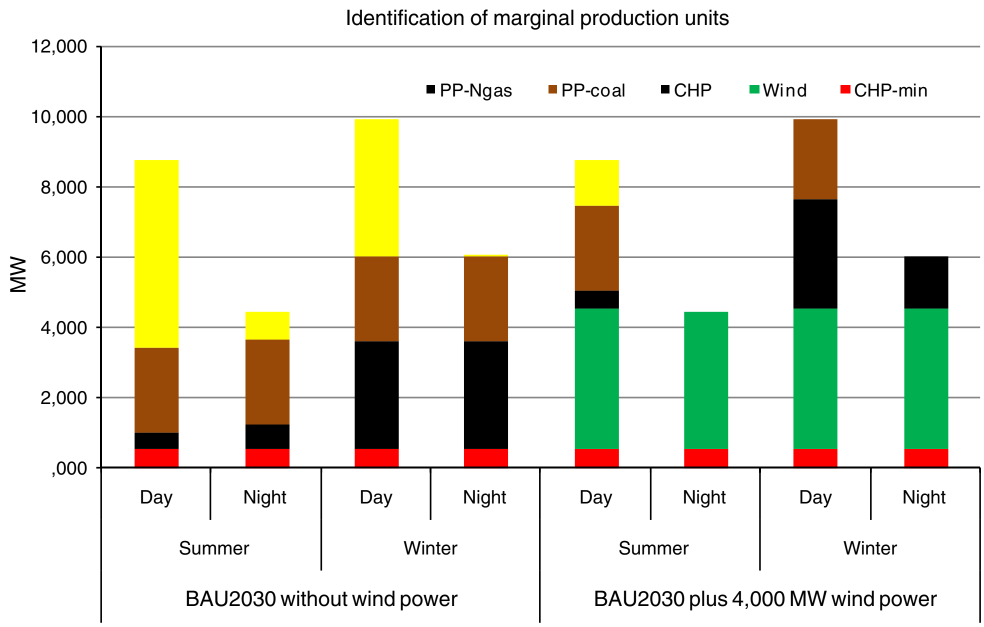

Fig. 1 Temporal differences in the production of electricity between summer and winter, day and night for one specific hour. The differences are illustrated in a business-as-usual (BAU) energy system, with and without wind power

according to their short-term marginal costs in the following order:

1. Wind power
2. CHP plant
3. Coal-fired power plant (PP)
4. Natural gas-fired PP

Figure 1 illustrates how the marginal production units shift from one hour to another, here illustrated by summer/winter and day/night hours. In the three first columns, the contribution from prioritised production such as wind power and CHP is low, and the marginal production is represented by natural gas-fired power stations. In column 4, the heat demand and thereby the CHP production is so high that the marginal production unit shifts to coal-fired PP. If wind power production is high, as in columns 4–8, the marginal production unit may be the CHP plants or even wind power itself.

As illustrated by Fig. 1, the impact of reducing the electricity demand differs from one hour to another. Moreover, the impact also differs from one energy system to another and especially becomes complex if the system involves CHP and fluctuating renewable energy sources such as wind power. Due to climate change, the policy in many countries around the world is to convert energy systems into sustainable systems, which in many cases involve CHP and renewable energy. Recently, the European Union decided on the 2020 agreement involving both 20–30% renewable energy and a 20% cut in CO_2 emissions by 2020. Such policy involves the improvement of energy efficiency as well as the expansion of CHP. In this regard, the Danish energy system, currently with a 20% share of wind power and a 50% share of CHP, is a front-runner in the development of such future sustainable energy systems.

The Danish energy system is a mix of different technologies involving large steam turbine extraction PP based on coal or natural gas as well as small distributed CHP and wind power producers. The share of CHP is approximately 50% of the annual electricity production, and consequently, the production of electricity is often constrained by the heat demand. Furthermore, the use of wind power introduces a source to the system which produces independently of present demands. The system is not isolated but does exchange electricity on the Nordic Nord Pool market depending on the costs of the marginal electricity production. When wind fluctuations lead to lower electricity market prices in Denmark, the electricity is exported to Norway/Sweden and vice versa when wind power production is low and/or hydropower available and produced in the Nordic system. But there are constraints to such exchange. The grid cannot transport all the energy demanded, and the electricity exchange within this market is furthermore dependent on the price level and differences in electricity prices on the Nordic market.

The long term-objective of the Danish Government and Parliament is to convert to a 100% renewable energy supply. The first decision to increase wind power even more has already been made and is being implemented. Such aim has raised the question of how to design the system in order to integrate even very high shares of wind power. In other countries, efforts are also being made to increase the share of wind power and CHP. Various studies on different technologies have been done including better regulation of distributed CHP plants (Andersen and Lund 2007; Lund 2003; Lund and Andersen 2004; Lund and Munster 2006a) and the utilisation

of waste (Münster 2007), electric boilers, heat pumps, fuel cells, hydrogen storage (Blarke and Lund 2007) and compressed air energy storage (Lund et al. 2009; Salgi and Lund 2008). Moreover, the integration of transportation (Lund and Munster 2006b; Mathiesen et al. 2008) and the design of the electric grid have been analysed (Alberg Ostergaard 2003; Lund 2005). Such new technologies are important to the integration of fluctuating renewable energy sources. However, they also make the identification of environmental impacts of marginal changes on electricity demands even more complex.

2 Purpose of the study

The purpose of this study was to determine the YAM electricity production considering the fact that the affected technologies shift from one hour to another depending on variations in both heat and power demand and variations in electricity production from, e.g. wind power.

Our hypothesis is that the constraints and fluctuations of real-life energy systems create a situation in which the de facto marginal source of electricity production is not coal or natural gas but a mixture of different technologies using different fuels.

A strict distinction is made between, on the one hand, marginal capacities, i.e. the long-term change in PP capacities, and, on the other, marginal productions, i.e. the changes in production given the combination of PP and their individual marginal production costs. Detailed energy system analysis simulation is used to identify the affected technologies, i.e. the marginal consequences at each hour of the year. On the basis of such input, a YAM is identified and the environmental impacts are calculated using data from ecoinvent.

The functional unit is 1 kWh of electricity produced in Denmark and delivered to a Danish consumer, including exchange on the Nordic electricity market. The aim of the study was also to calculate the extent of the environmental impacts related to the consumption of 1 kWh of marginal electricity as a yearly average value based on the hour-by-hour fluctuations in the Danish Energy System.

3 Materials and methods

The methodology applied involves the definition of a relevant energy system as well as the choice of an energy system analysis model and an LCA tool.

3.1 The Danish energy system, BAU2030

The environmental impacts of marginal changes in electricity production depend in nature on the design of the specific energy system. Both the type and size of the electricity production and consumption units as well as the design of market regulation determine the result. The system description will have to include the heat sector and even the transport sector if, e.g. CHP units, heat pumps or electric vehicles are part of the system.

Here, the Danish Energy System is chosen for the analyses due to the fact that the system has a high share of CHP and wind power. These characteristics make the Danish system well suited for illustrating the aim of this study. Moreover, the Danish system represents a case which may correspond to future systems in other countries.

In order to calculate the long-term marginal production change, a business-as-usual projection to year 2030 has been used, as presented by the Danish Energy Authority (BAU2030; The Danish Ministry of Transport and Energy 2005b). The projection assumes no active policy apart from decisions already made when the analysis was conducted. Such a system is very similar to the present energy system in Denmark. However, various demands including the electricity demand have increased, and a small increase in wind power together with a number of new PP has replaced old power stations. Moreover, the mixture of coal-fired steam turbine power stations and natural gas-fired combined cycle power stations is important for the analysis. This is one of many systems made by the Danish Energy Authority projecting a BAU energy system. The BAU2030 used here assumes that coal PPs are replaced by natural gas PPs and rather low fuel prices compared to the present recommendations from the International Energy Agency.

Three economic factors are especially important to the market economic behaviour of the individual plants and thereby to the system: fuel prices including taxes, external electricity market prices and CO_2 emission trade prices. Here, all three factors are defined in accordance with assumptions made by the Danish Energy Authority in 2006. However, in this paper, the expected future fuel prices relate to three different expectations to the future oil price level, as shown in Table 1. In the analysis, the system responses have been analysed for all three sets of fuel prices, and an average respond has been calculated. Such average represents the assumption that oil prices will continue to go both up and down. The fuel prices represent costs on the international market and transportation and handling costs are added, as shown in Table 2. In Table 2, taxes representing the present Danish taxes on fuel for, e.g. heat production and electricity for heat pumps and electric heating are included. The authorities expect the future CO_2 emission trade price to be 20 euro/ton.

It should be emphasised that the CO_2 emission trade price does not represent the external costs of pollution and climate change. Such externalities are substantially higher. Here, the market price is solely used in order to identify the

Table 1 Fuel costs dependent on price per barrel

EUR/GJ	Crude oil	Coal	Natural gas	Fuel oil	Gas oil diesel	Petrol JP	Biomass
\$40/bbl	5.5	1.7	4.3	3.9	6.9	7.3	2.9
\$68/bbl	9.4	2.0	6.3	6.6	11.7	12.5	2.9
\$96/bbl	13.2	2.4	8.3	9.3	16.5	17.6	2.9

operational marginal changes of the electricity production units.

Such combination of taxes and fuel and CO_2 quota costs leads to the important overall assumption that the short-term and long-term marginal production costs of coal-fired plants are lower than those of natural gas-fired plants.

An important factor when modelling energy systems on international markets is represented by the exchange capacities. In the analyses, the planned new transmission line between the two energy systems in Denmark is assumed to be implemented. A technical limit of international transmission lines in or out of Denmark of 2,500 MW is used here. This transmission capacity is higher in reality but is restricted due to different limitations in the surrounding grids (Lund and Mathiesen 2006b).

3.2 Energy system analysis tool: EnergyPLAN

For the analysis, the EnergyPLAN model is used. The model is a general energy system analysis tool designed for analysing regional or national energy systems. It is an input–output model which uses data on capacities and efficiencies of the energy conversion units of the system and the availability of fuels and renewable energy inputs. Hour by hour, it calculates how the electricity and heat demands of the complete system will be met under the given constraints and regulation strategies. In such analyses, the model has a library of, e.g. wind power hour distributions based on actual historical productions from Danish wind turbines. Figure 2 gives an impression of the function of the model. It is seen how it focuses on the electrical system but incorporates other parts of the system which interact with it.

The result of the calculation is a detailed knowledge of the production of the different units including the production of marginal changes in electricity demands. From this, fuel consumption and fixed and variable operation costs can be calculated, and subsequently, the system economic costs and CO_2 emissions caused by meeting the demands of society can be found.

The modelling tool allows for different types of regulation strategies divided into two main categories. The first category is a technical regulation in which the strategy is to achieve an optimum of least fuel consumption. In such a strategy, CHP is given priority. The second regulation strategy is a market economic regulation in which all units are operated in order to optimise operational income. In such regulation strategy, each plant compares the marginal production costs to the electricity market price of the given hour.

All strategies can be analysed for a closed system as well as an open system with transmission lines to an external international electricity market. On the closed market, the electricity prices are determined by the production costs of the marginal production unit at the given hour. On the open market, such price setting interacts with price fluctuations on the external market including the division of markets in the case of transmission bottlenecks. The latter allows for the analyses of the influence which different operation circumstances may have on the price settings on the external market, e.g. the influence on the Nordic Nord Pool market of 'wet' and 'dry' years with regard to the share of hydropower.

The model has previously been used in a number of energy system analysis activities, including expert committee work for the Danish Energy Authorities and NGOs as well as the design of 100% renewable energy systems (Lund and Münster 2003a, b; Lund and Mathiesen 2006a; Lund 2007b; Lund and Mathiesen 2010). More information on the model can be found in (Lund and Münster 2003a, b; Lund 2007a). The present version 7.0 of the EnergyPLAN model including documentation can be downloaded freely from the following home page: www.EnergyPLAN.eu.

Table 2 Fuel handling costs per GJ

EUR/GJ	Coal	Natural gas	Fuel oil	Gas oil diesel	Petrol JP	Biomass
Power stations (central)	0.1	0.4	0.2			1.6
Distributed CHP, district heating and industry		0.9	1.8			1.1
Individual households		2.1		2.8		6.1
Road transportation				3.0	4.1	
Air planes					0.7	

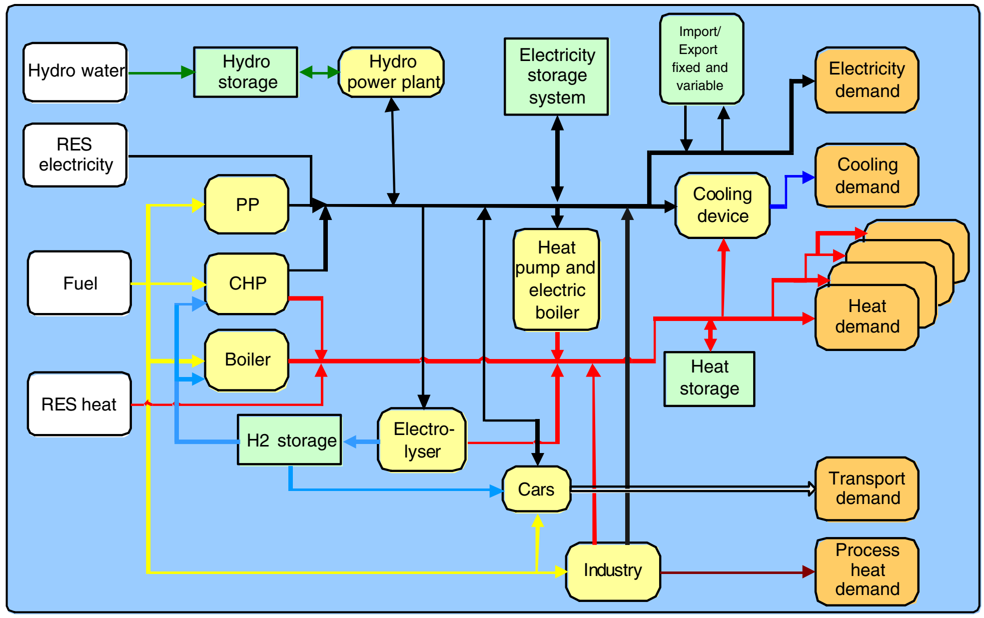

Fig. 2 EnergyPLAN energy system analysis model (see: www.energyPLAN.eu). RES electricity and RES heat represent intermittent renewable energy sources such as onshore and offshore wind power, photo voltaic, wave power and solar thermal

3.3 LCA approach and tool

A proper identification and delimitation of the analysed product system like the Danish energy system are seen as increasingly important to the outcome and quality of the LCA (Weidema 2003; Ekvall and Weidema 2004). Two different approaches can be used for that purpose: consequential LCA and attributional LCA. This study uses the consequential approach which is comprehensively described in Weidema (2003) and Ekvall and Weidema (2004). Consequential LCA differs from attributional LCA in two ways: (1) The processes included are those which are most likely to respond to a change in demand, and (2) co-product allocation is avoided by system expansion (Schmidt and Weidema 2008). These two premises are fulfilled by using the EnergyPLAN model. Today, many LCAs are based on the consequential approach (Dalgaard et al. 2008; Schmidt and Weidema 2008; Thrane 2004). Consequential LCA has more or less become the official guideline for system delimitation in LCA in Denmark (Weidema 2003).

According to Ekvall and Weidema (2004), a marginal technology is identified through five steps: (a) definition of time horizon of the decision to be supported by the LCA, (b) determination if the process affected is specific or related to the overall market, (c) identification of the market trend, (d) identification of constrained technologies, and (e) identification of the actually affected technology. The first step determines whether to include production capacity (long term) or only focus on existing production capacity (short term). If the affected process in (b) is a specific technology, then this is the marginal technology. The market trend (c) determines whether the marginal technology is to be found among the most competitive suppliers (increasing/constant market trend) or the least competitive suppliers (decreasing market trend). In step (d), constrained technologies are eliminated from the list of candidates for the marginal technology. Technologies can be constrained for several reasons: quotas, emission limit values, physical conditions, political constraints or the demand for co-products. Finally, in step (e), the marginal technology is identified according to the premises given in steps (a) to (d).

In attributional LCA, electricity supply is commonly modelled as an average of all electricity sources within the region (ecoinvent 2004), whilst consequential LCA often points to either coal or natural gas (Weidema 2003; Schmidt et al. 2004; Frees and Weidema 1998). In this study, the marginal technologies are affected at two stages.

Firstly, the marginal technology affected as a consequence of a change in demand is identified. This corresponds to the traditional identification of marginal technologies in consequential LCA as described above.

Secondly, the technologies affected as a consequence of change in capacity of a certain technology in the energy system are modelled. The model output is not one technology as in traditional consequential LCA, but the marginal technology includes several technologies. We define an average marginal of the year (YAM) on an hour-by-hour basis. The YAM is found on the basis of the consequential methodology, but it also offers other LCA studies a feasible 'marginal electricity' supply including different technologies, which work together in the actual Danish energy system.

The environmental impacts of the identified YAMs are evaluated. Among the different methods available for assessing the environmental impacts of the different energy technologies used, we have applied the EDIP97 (Hauschild and Wenzel 1998; Wenzel et al. 1997). In this method, a

number of impact categories are considered of which we have chosen to include global warming, ozone depletion, acidification, eutrophication and photochemical smog.

The method is implemented in the PC tool SimaPro 7.1 (Simapro 2007). EDIP97 also includes human toxicity, ecotoxicity, waste and resource use, but we have chosen not to include these categories in the evaluation of environmental impacts.

Two kinds of energy system analyses have been conducted. In the first, the energy systems have been compared in a 'closed market' situation in which electricity is not exchanged on external international electricity markets. Secondly, the system has been analysed in an open market system exchanging electricity on the Nordic Nord Pool electricity market.

An increase in demand is assumed to be the general market trend. Three different kinds of marginal changes in capacities have been analysed, namely wind power, natural gas and coal PP capacity. Also, a situation with no changes in capacity caused by changes in production is analysed. For each 1 kWh/year, the change in capacity corresponds to 0.2 W (or 200 MW for each 1 TWh/year) including approximately 10% reserve capacity, which is equivalent to the present amount of reserve capacity. For wind power, a 340-MW mixture of onshore and offshore wind power equals the annual production of 1 TWh in a normal wind year. For each of such marginal changes in capacity, the marginal operational consequences have been found. The results are found by calculating the total system hour by hour including electricity and heat supply and comparing the results to a similar analysis with no marginal changes in capacity. Here, the analysis is conducted with a reduced demand. However, similar marginal consequences will be visible in a situation with an increased demand.

4 Results

4.1 Energy system analysis

The systems respond to the changes in electricity demand in various ways depending on the situation at each hour. At all hours, the different energy plants compete on marginal production costs on the electricity market. PP can respond by decreasing production if such plants are operated at the given hour. CHP plants can decrease production by replacing heat production by heat from the heat storage or the peak load boiler. Such responds will occur if the marginal production costs exceed the market price and if such change does not violate the restriction of maintaining grid stability in the system.

At some hours, wind power in combination with restricted minimum production on CHP and PP units will result in excess electricity production, i.e. when the resulting production exceeds the demand at a certain hour. In such situation, the system is told to utilise excess production first by replacing heat production in district heating systems by electric boilers and, secondly, by stopping some wind turbines (wind).

The results of the analysis of operational changes in a closed system are shown in Fig. 3. In all situations, the marginal response is a combination of changes in operation of several types of plants. The reason for this is the fact that the marginal unit differs from one hour to another.

In the situation in which the marginal change in capacity takes place at the natural gas PP ('BAU + PP-Ngas' in Fig. 3), the system responds at most hours by decreasing the production of coal-fired PP. Such responses represent the hours at which coal-fired power stations constitute the marginal. However, at other hours, when coal PP production, which has the lowest short-term marginal costs, reaches the limit, natural gas PP constitutes the marginal. Again, at other hours, the CHP plants constitute the marginal. Finally, at a small number of hours, the change in demand changes the number of hours of excess production and thereby the use of electric boilers and the stopping of wind turbines. In terms of fuel, the marginal in such system comprises a mixture of coal and natural gas. In the system with no change in capacity ('BAU + None' in Fig. 3), the mechanism is the same as for the system with extra natural gas PP capacity because of the fuel prices used and the capacities of the energy system analysed.

In the situation in which the marginal change in capacity takes place at coal-fired PP ('BAU + PP-Coal' in Fig. 3), the operational impact is the result of the combination of two influences. The one is the same as described for the 'BAU + PP-Ngas' situation above. The other is the decrease in coal capacity which at certain hours leads to an increase in the production of the natural gas PP. In terms of fuel, the result is almost only coal. The reason for this is the fact that the extra amount of natural gas consumed at the PP at some hours seems to correspond to the natural gas saved in the distributed CHPs at other hours.

In the situation in which the marginal change in capacity relates to wind power ('BAU + PP-Wind' in Fig. 3), the operational impact is influenced by the change in wind power production. However, at some hours, the decrease in wind power production is smaller than the decrease in demand, and consequently, the CHP plants have to decrease their production. At other hours, the decrease in wind power is larger than the decrease in demand, and consequently, the power stations have to increase their production.

The analysis of impacts of marginal increases in electricity demand in an open system has also been made for the projected BAU2030 system. No doubt remains that in an open system, changes in demand will lead to changes in import and export of electricity between Denmark and the rest of the Nordic system. However, when making such

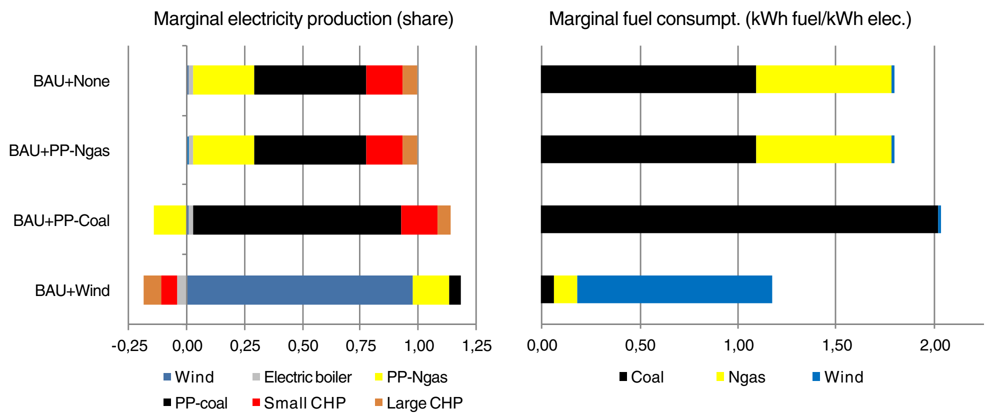

Fig. 3 Marginal production changes when increasing demands by 1 unit (TWh/year) of electricity in a closed Danish energy system with marginal change in either 340-MW wind, 200-MW natural gas or 200-MW coal-fired power plant capacity and in a situation with no change in capacity

analysis, it is important to distinguish between two different situations. On the one hand, changes in the electricity demand in Denmark may cause changes in the annual production of units in the rest of the Nordic system. On the other hand, such change in exchange will cause only a relocation of the hours at which the hydropower plant chooses to place the total production, which is solely restricted by the amount of water.

Here, the analysis has been made assuming that:

- The nuclear power production in the Nordic system will not change since such production has very low short-term marginal production costs and is consequently prioritised on the market in line with wind power production.
- The annual hydro power production will not change. Such annual production depends solely on the amount of water in the reservoirs. However, the decision of when hydropower will produce electricity will change. Production will be decreased at hours with low prices and increased at hours with high prices.
- The marginal PP production may change in the same way as the production of coal-fired and natural gas-fired PP in Denmark. However, in accordance with the design of the BAU2030 system, the marginal PP capacity in the Nordic system is assumed to be natural gas combined cycle PP in Norway, as already represented in the analysis of the Danish system.

A detailed explanation for why such impact is a probable result of the present market organisation is given in Kofoed-Wiuff et al. (2007). Based on these assumptions, the analysis of the marginal changes in an open system has been carried out by adding a hydropower system to the calculations above. The exchange with such system in both ways (import/export) has been limited to the capacity of 2,500 MW equal to the available exchange capacity in the existing transmission lines. The Nordic system hereby influences the Danish system by storing electricity at some hours and delivering the same amount at other hours.

The results of the analysis of the open system are shown in Fig. 4. When comparing this to Fig. 3, one can see that in the open system, the share of coal power increases and the share of natural gas decreases. However, even in the open system, the average changes are still a mixture. There are two main reasons for this. First, the limitations in coal-fired capacity still create a situation in which natural gas is the marginal production. Secondly, the limited capacity of the transmission lines hinders the hydropower in Norway from absorbing all the power produced at the natural gas PP.

4.2 The YAM in an open energy system

In Figs. 3 and 4, the share of change in electricity production by definition sums up to 100% of 1 unit. However, one of the changes is the use of electricity in electric boilers and another is the change in electricity produced by CHP. Both such changes have consequences for the district heating since changes in heat production from CHP or electric boiler will be met by changes in the peak load fuel boiler production. Consequently, when calculating the YAM, one will have to leave out the electric boiler and instead include the changes in the peak load boilers. Based on this, it can be concluded that the YAM has the properties described in Table 3.

Table 3 shows significant differences between the changes in capacity and the actual long-term changes in production. In order to calculate the environmental impacts of 1-kWh marginal electricity, the relative contributions of technologies used for producing an extra kilowatt-hour is transformed into an average figure of environmental impact emanating from the use of this mix of technologies.

The information on environmental impacts is taken directly from the ecoinvent database. This information concerns the impacts from the whole life cycle of the technology in question, i.e. also entailing impacts of production of facilities, transportation of fuels and demolition of facilities at the end of the lifetime of these technologies. Looking only at the five impact categories—

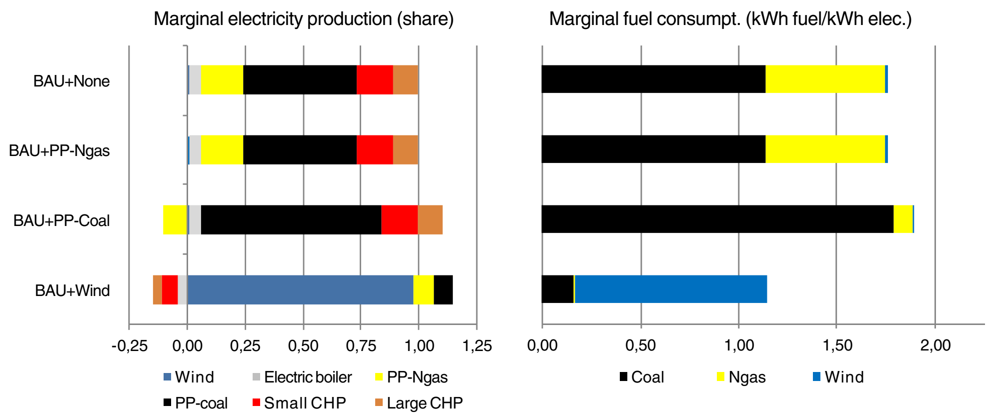

Fig. 4 Marginal production changes when increasing demands by 1 unit (TWh/year) of electricity in an open Danish energy system with marginal change in 340-MW wind, 200-MW natural gas or 200-MW coal-fired power plant capacities and in a situation with no change in capacity

global warming, ozone depletion, acidification, eutrophication and photochemical smog—we can easily depict the impacts of each of the eight marginal technologies used in Table 3. The results of one of the analyses are presented in detail in Table 4.

The purpose of the modelled YAMs is to provide a well-justified estimate of the actual production affected by a change in demand. In a traditional consequential LCA, this is identified as either the production of coal PP or natural gas PP, and this is assumed to be the only affected technology. In this article, it is acknowledged that the installation of, e.g. coal PP capacity will also lead to changes in the production of other technologies because the entities in an energy system are connected. A change in demand of 1-kWh electricity has been modelled for four different situations, producing the change (1) without changing the capacity, (2) by installing natural gas PP, (3) by installing coal PP and (4) by installing wind turbine capacity. These are compared with the traditional way of identifying the marginal technology in consequential LCA, e.g. either coal PP or natural gas PP, in Table 5. Also, the Danish production mix from the year 2000 in the ecoinvent database is presented.

5 Discussion

The four analyses and examples of YAMs in Tables 3 and 5 have been used in order to present examples of the cause–effect chain between a change in demand for electricity and

Table 3 Energy system analysis results of the change of one unit (TWh/year) meeting electricity demand in an open energy system

	BAU2030	BAU + PP-Ngas	BAU + P-coal	BAU + wind
Change in investments (capacity)				
Ngas combined cycle		200 MW		
Coal power plant			200 MW	
Wind turbines				340 MW
Average change in electricity production (share)				
Wind turbine	0.01	0.01	0.01	0.98
PP-coal	0.49	0.49	0.78	0.08
PP-Ngas	0.18	0.18	−0.11	0.09
Large-CHP Ngas	0.09	0.09	0.09	−0.03
Large-CHP coal	0.02	0.02	0.02	−0.01
Small-CHP Ngas	0.16	0.16	0.16	−0.07
EH (electric boiler)	0.05	0.05	0.05	−0.04
Sum	1.00	1.00	1.00	1.00
Average change in heat production (unit heat/unit elec.)				
Large-CHP coal	0.13	0.13	0.13	−0.05
Small-CHP Ngas	0.20	0.20	0.20	−0.08
EH (electric boiler)	−0.05	−0.05	−0.05	0.04
Boiler coal	−0.16	−0.16	−0.16	0.05
Boiler Ngas	−0.12	−0.12	−0.12	0.04
Sum	0.00	0.00	0.00	0.00

Table 4 Detailed information on the five environmental impact categories for the BAU + PP-Ngas YAM

BAU + PP-Ngas	Global warming	Ozone depletion	Acidification	Eutrophication	Photochemical smog
Unit	(CO_2-eq)	(CFC11-eq)	(SO_2-eq)	(NO_3-eq)	(ethane-eq)
PP-Ngas (200 MW, 30 years)	9.92E−01	8.03E−08	7.35E−03	7.54E−03	5.47E−04
Wind turbine (elec.)	1.43E−01	8.24E−09	7.77E−04	8.94E−04	6.50E−05
PP-Coal (elec.)	434	1.36E−06	9.28E−01	5.70E−01	2.72E−02
PP-Ngas (elec.)	77.4	9.46E−06	6.77E−02	7.80E−02	1.27E−02
Large CHP Ngas (elec.)	53.6	6.55E−06	4.69E−02	5.41E−02	8.78E−03
Large CHP Coal (elec.)	19.4	6.08E−08	4.16E−02	2.55E−02	1.22E−03
Small CHP Ngas (elec.)	105	1.17E−05	1.63E−01	2.47E−01	2.57E−02
Boiler Coal (heat)	−74.4	−2.86E−07	−5.34E−01	−2.48E−01	−9.38E−03
Boiler Ngas (heat)	−38.0	−4.56E−06	−3.73E−02	−3.82E−02	−6.09E−03
Electric boiler	0.00	0.00	0.00	0.00	0.00
Total (YAM)	578	2.44E−05	6.84E−01	6.97E−01	6.07E−02

the installation of new capacity. This relation is very complex and has only been performed for one specific projection of the 2030 energy system. We have provided the results of four different situations in order to keep open the possibilities for further analysis of what can be considered the marginal technology. Here, we will present an example to illustrate why the identification of the marginal capacity to be installed is very complex. As mentioned in Section 3.1, natural gas PP replaces coal PP in the BAU2030 used in these analyses. This is based on fuel prices corresponding to an oil price of $28 per barrel (bbl) and a CO_2 emission trade price of 20€/ton (The Danish Ministry of Transport and Energy 2005a). According to the Energy Strategy 2025 of the Danish Ministry of Transport and Energy, biomass will replace coal in the case with high fuel and high CO_2 quota prices. With high fuel prices and low CO_2 quota prices, not many changes will occur and coal will remain competitive. In 2007 and 2008, fuel prices were higher than the 'high fuel price' scenario presented by the Danish Ministry of Transport and Energy and much higher than the expected 28/bbl. This illustrates the fact that the marginal capacity installed is heavily dependent on external factors such as future fuel prices and CO_2 quota prices. But also political decisions may affect the marginal capacity to be installed.

We suggest that the technology mix with the installation of natural gas or coal PP is used as the marginal capacity. The natural gas PP reflects the assumptions in the business-as-usual (BAU2030) scenario from the Danish Energy Authority. It is, however, likely that this will change as the BAU2030 system was made in 2005 and is based on rather low fuel prices. Considering the high fuel prices of recent years, the long-term marginal capacity is most likely to be wind, coal PP or potentially biomass. Also, it is rather uncertain if the long-term general demand will increase as increased international and national efforts promote energy savings.

The modelled YAMs are also compared with the electricity production most often applied in consequential LCAs, i.e. either coal PP or natural gas PP, as well as the average Danish electricity supply in 2000 (ecoinvent 2004), representing applied electricity in attributional LCA. The results of the four YAMs and the results of the three additional scenarios show significant differences. This

Table 5 YAM of 1 KWh of the four situations analysed and three examples of technologies which are traditionally used in consequential LCA

YAM Unit	Global warming (CO_2-eq)	Ozone depletion (CFC11-eq)	Acidification (SO_2-eq)	Eutrophication (NO_3-eq)	Photochemical smog (ethane-eq)
BAU	577	2.43E−05	6.77E−01	6.89E−01	6.02E−02
BAU + PP-Ngas	578	2.44E−05	6.84E−01	6.97E−01	6.07E−02
BAU + PP-coal	712	1.00E−05	1.13	9.15E−01	5.70E−02
BAU + Wind	83.3	−1,16E−07	3,22E−01	1,64E−01	6,93E−03
Traditionally used technologies in consequential LCA					
PP-coal only	885	2.77E−06	1.89	1.16	5.56E−02
PP-Ngas only	429	5.25E−05	3.76E−01	4.33E−01	7.04E−02
DK 2000 mix	694	3.18E−05	2.40	1.35	7.23E−02

underpins the importance of using a well-justified applied mix of electricity technologies in LCA studies.

6 Conclusions

This paper has addressed the identification of the environmental impacts of marginal electricity supplies on the basis of consequential LCA. According to the methodology, the environmental impacts can be examined by identifying the activities affected, i.e. often one marginal technology. The present 'state-of the-art' is to identify the long-term change in capacity, known as the long-term marginal technology, and assume that the marginal supply will be fully produced at such capacity. However, the marginal change in capacity will have to operate as an integrated part of the total energy system, and consequently, it does not necessarily represent the marginal change in electricity supply which is likely to involve a mixture of different production technologies.

Especially when planning future sustainable energy systems involving CHP and fluctuating renewable energy sources, such issue becomes very important. Therefore, a BAU2030 projection of the Danish energy system has been used as a case. With a high share of both CHP and wind power, such system can be regarded a front-runner in the development of future sustainable energy systems in general.

A strict distinction is made between, on the one hand, marginal capacities, i.e. the long-term change in PP capacities, and on the other, marginal productions, i.e. the changes in production given the combination of PP and their individual marginal production costs. Detailed energy system analysis (ESA) simulation has been used to identify the affected technologies considering the fact that the marginal technology will change from one hour to another depending on the size of electricity demand compared to, among others, wind power and CHP productions. On the basis of such input, a long-term YAM technology has been identified and the environmental impacts are calculated using data from ecoinvent.

The results show that the marginal electricity production is not based solely on the marginal change in capacity but can be characterised as a complex set of affected electricity and heat technologies. Consequently, this paper recommends a combination of LCA and ESA as a methodology for identifying a complex set of marginal energy technologies. The same conclusion would probably go for other marginal technologies used in LCA modelling as, e.g. marginal crops, marginal aluminium and so on. The presented results merit a further investigation of this type of composite or complex marginals.

A long-term YAM technology has been calculated for the Danish BAU2030 system in the case of three different long-term marginal changes in capacity, namely coal, natural gas or wind power. Such YAMs have been compared to previously established environmental impacts, and the results have been discussed. On the basis of this discussion, the paper advocates the use of YAM instead of previously used impact indicators. When choosing among the different YAMs, this paper points out the fact that the relevant data to use in an LCA based on a BAU2030 system will be the data which assume marginal capacity changes in natural gas-fired PP. However, depending on the purpose of the specific study, one may advocate that marginal capacity changes in wind power or coal PP may be more relevant. In all cases, sensitivity analyses are recommended.

Acknowledgements The work presented in this paper is a result of the research project Coherent Energy and Environmental System Analysis (CEESA), partly financed by The Danish Council for Strategic Research.

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